THE ASTROPHYSICAL JOURNAL, 255:L81–L84, 1982 April 1

A HIGH-RESOLUTION MEASUREMENT OF THE 2.223 MeV NEUTRON CAPTURE LINE IN A SOLAR FLARE

THOMAS A. PRINCE
California Institute of Technology
AND
JAMES C. LING, WILLIAM A. MAHONEY, GUENTER R. RIEGLER, AND ALLAN S. JACOBSON
Jet Propulsion Laboratory, California Institute of Technology
Received 1981 November 4; accepted 1981 December 23

ABSTRACT

An intense solar flare lasting 40 s was observed by the *HEAO 3* γ-ray spectrometer on 1979 November 9 at 3:05 UT. The flare was observed in four high-resolution germanium detectors as well as in five CsI shield detectors over an energy range of 100 keV to above 5 MeV. Of particular interest is a line feature at 2.2248 ± 0.0010 MeV. The precise energy measurement provides unambiguous evidence that this is the $^1H(n, \gamma)^2H$ line resulting from neutron capture on hydrogen. An upper limit of 5 keV is found for the natural line width. The time dependence of the neutron capture line is discussed as well as the overall characteristics of the November 9 flare.

Subject headings: gamma rays: general — Sun: flares

I. INTRODUCTION

Gamma-ray lines provide a direct observational probe of nucleon acceleration in solar flares. Until recently, most of the information relating to the acceleration of nuclei in flares has come from the study of solar energetic particles at 1 AU. From these measurements, the energy spectrum and the composition of the accelerated particles can be inferred once the effects of interplanetary propagation have been accounted for. Gamma-ray line observations promise to yield significant new information by providing a temporal history of nucleon acceleration during the flare and by indicating the conditions of the ambient solar medium through which the flare propagates.

From both experimental observations and theoretical considerations, the most intense γ-ray line from solar flares is expected to be the neutron capture line at 2.223 MeV. Emission at this energy occurs through the $^1H(n, \gamma)^2H$ reaction when neutrons produced by energetic proton and alpha interactions propagate into the photosphere and are captured on ambient hydrogen. Early investigations of these processes were undertaken by Lingenfelter and Ramaty (1967), and detailed Monte Carlo studies were later carried out by Wang and Ramaty (1974, 1975). Reviews concerning this subject have been written by Ramaty, Kozlovsky, and Lingenfelter (1975), and Ramaty *et al.* (1979). The chain of production, propagation, capture, and subsequent photon transport depends upon a number of parameters, including the temperature and density profile of the photosphere and chromosphere, the shape of the energetic proton spectrum, and the ^{3}He abundance in the photosphere. As a consequence, observations of the 2.223 MeV neutron capture line can in principle be used to measure these parameters. To carry this out in practice, however, requires that the models for the production of the line first be tested quantitatively against experiment.

Prior to the recent solar maximum period, the neutron capture line had been seen in three solar flares (Chupp *et al.* 1973; Chupp, Forrest, and Suri 1975; Hudson *et al.* 1980). The solar maximum period has tripled the number of observed occurrences of this line. In addition to the observation by the *HEAO 3* γ-ray spectrometer reported here, there have been numerous observations of 2.22 MeV line emission by the γ-ray experiment on board the *Solar Maximum Mission* spacecraft (cf. Chupp *et al.* 1981; Chupp 1981).

The measurement discussed in this *Letter* is unique in that it is the first observation of the neutron capture line from a solar flare with a high-resolution detector (FWHM ~ 7 keV), allowing a more precise determination of energy and line width. In addition, the very short, impulsive nature of the November 9 flare combined with the relatively high flux of 2.223 MeV line emission allows an upper limit to be placed on the time scale of the buildup of the line.

II. INSTRUMENTATION

The *HEAO 3* high-resolution γ-ray spectrometer is described in detail by Mahoney *et al.* (1980). The instrument consists of a cluster of four high-purity germanium detectors surrounded by a segmented anticoincidence shield of CsI 6.6 cm thick. Both the germanium detectors and the CsI shield can be used to make solar flare observations. The germanium detectors are sensitive in the energy range of 50 keV to 10 MeV. The shields present a total of 900 cm^2 of geometric area to the Sun and provide information on three integral count rates: above 80 keV, between 420 and 580 keV, and above 3.8 MeV. The primary mission of the *HEAO 3* γ-ray spectrometer is to perform an all-sky survey of low-energy γ-ray emission, and consequently the experiment was not optimized for solar flare studies. The pointing of the instrument is such that the telescope nominally looks in a direction 90° away from the Sun. This effectively limits high-resolution measurements with the germanium detectors to energies greater than approximately 1 MeV, where the attenuation by the shield is at its minimum. Fortunately, this energy range includes the important 2.223 MeV line, whose transmission through the shield is 27%. The combined effective area of the two germanium detectors on the sunward side of the spectrometer is 2.6 cm^2 at this energy.

III. THE SOLAR FLARE OF 1979 NOVEMBER 9

A short, impulsive γ-ray event lasting approximately 40 s was observed by the *HEAO 3* γ-ray spectrometer at 3:05 UT on 1979 November 9. The γ-ray emission was concurrent with a 1B optical flare and an M9 class X-ray flare from active region 2099 at latitude S12 and longitude W02 on the Sun. This is the same region that produced an intense γ-ray continuum event a day earlier (Riegler *et al.* 1982), as well as a smaller γ-ray event 3 hr after the 3:05 UT flare, and numerous other X and M class X-ray events. The X-ray, optical, and γ-ray emission was also accompanied by rather intense microwave emission (6000 solar flux units at 15.4 GHz), Type II ("herringbone") and Type III radio emission, and hard X-ray emission (observed by the MONEX experiment on the *P78-1* satellite; Landecker 1981). No large increases in interplanetary particle fluxes were observed following the November 9 flare.

The low-energy γ-ray flux above 80 keV observed by *HEAO 3* with a time resolution of 1.28 s is shown in Figure 1*a*. These photons are produced primarily in bremsstrahlung interactions of energetic electrons. While most of the previous γ-ray line-emitting flares (e.g., 1972 August 4, 7; 1977 November 22; and 1978 July 11) had low-energy γ-ray continuum emission with durations of 5–10 minutes and exhibited complex temporal structure, the flare of November 9 shows an essentially featureless spike with a total duration of approximately 40 s. This behavior is typical of a number of the flares early in the 1980–1981 solar maximum period (Ryan *et al.* 1981).

Figure 1*b* shows the high-energy γ-ray emission above 3.8 MeV. Although the data were obtained with a coarser 10.24 s time resolution, they indicate the same general

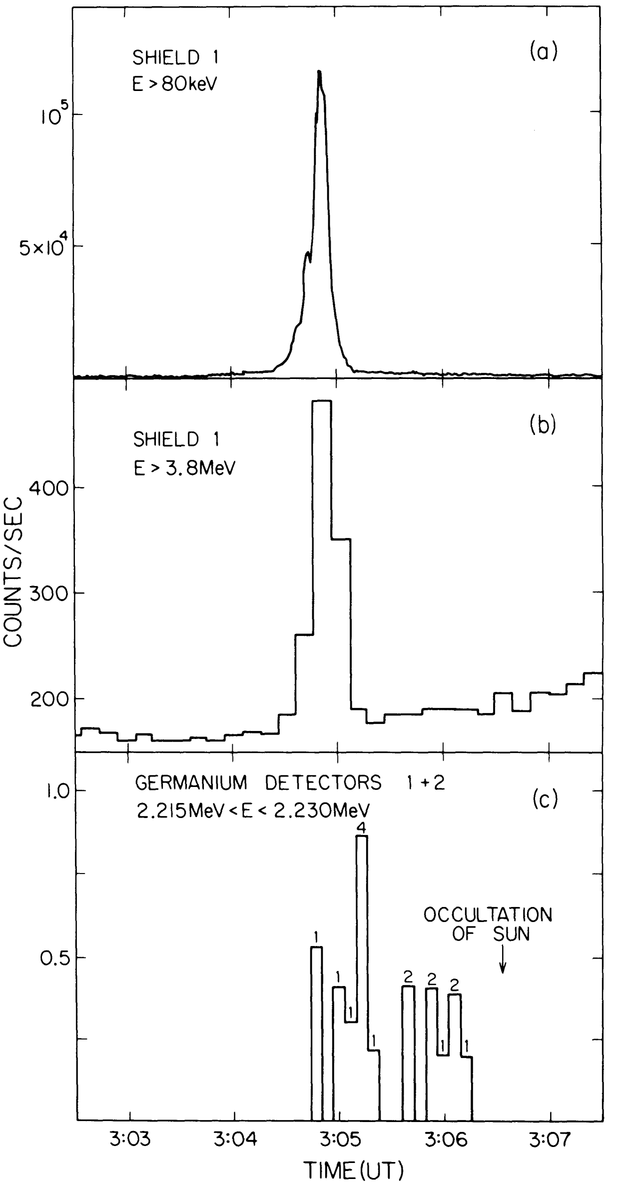

FIG. 1.—Temporal response of the CsI shield and germanium detectors to the 1979 November 9 solar flare. Dead time corrections have been applied to all count rates. Shield 1 and germanium detectors 1 and 2 are on the sunward side of the instrument. The actual number of counts registered in the germanium detectors during each 6.5 s time interval is indicated above the corresponding time bin.

time dependence as the low-energy flux. This is of interest because of suggestions (Ramaty *et al.* 1977) that the origin of the photon flux above 4 MeV in solar flares with line emission may be largely attributed to nucleonic processes rather than electron bremsstrahlung. If this is indeed the case, the observations of the low-energy and high-energy flux in the November 9 flare would indicate almost simultaneous acceleration (within 10 s) of the nucleon and relativistic electron components of the flare.

TABLE 1

1979 NOVEMBER 9, 3:05 UT SOLAR FLARE

Parameter	> 80 keV	> 3.8 MeV	2.223 MeV
Peak flux (photons cm^{-2} s^{-1})	480 ± 100	2.5 ± 0.2	...
Average flux (photons cm^{-2} s^{-1})	230 ± 25	1.23 ± 0.09	0.29 ± 0.07
Fluence (photons cm^{-2})	(1.1 ± 0.1) × 10^4	50 ± 4	> 38 ± 9

In spite of its short duration, the November 9 flare exhibited intense peak γ-ray fluxes, yielding a large total integrated γ-ray flux. The values for the peak, average, and total integrated fluxes above 80 keV and 3.8 MeV are given in Table 1. The total energy output of the flare above 80 keV is estimated to be at least 4.0 × 10^{24} ergs.

IV. 2.223 MeV LINE EMISSION

Figure 1*c* shows the time history of events recorded in the energy band 2.215–2.230 MeV from the two germanium detectors on the sunward side of the spectrometer. Evident in the figure is a flux of photons beginning near the time of flare maximum and continuing for at least 80 s following the peak of the flare. From the energy spectrum of Figure 2, it is clear that these events may be attributed to neutron capture on hydrogen which produces 2.223 MeV photons. Unfortunately, the entire time history of the 2.223 MeV emission could not be observed because the spacecraft passed into the Earth's shadow shortly after the flare event at 3:06:32 UT. As a consequence, the characteristic decay time of the line emission could not be determined.

If the models for the origin of the 2.223 MeV line are correct, the time scale for the buildup of the line should be determined primarily by the distribution of flight times between the site of production and the capture region. Since these times are expected to be on the order of a few seconds or less for production in the chromosphere and capture in the photosphere, the buildup of the line should take place on a short time scale, typically about 10 s for 1 MeV neutrons. The emission should then decay in a quasi-exponential fashion with a characteristic decay time of 20–200 s, depending on the neutron energy spectrum. Although the distribution of events in Figure 1*c* is statistically limited, the buildup of the distribution is consistent with the short time scales predicted by the models. One event is observed simultaneously with the peak of the flare (within 20 s of the onset), and half of the events detected during the 100 s observation interval following the flare arrived within 30 s of the peak of γ-ray continuum emission. The data therefore suggest an upper limit of 20 s for the buildup of the 2.223 MeV neutron capture line.

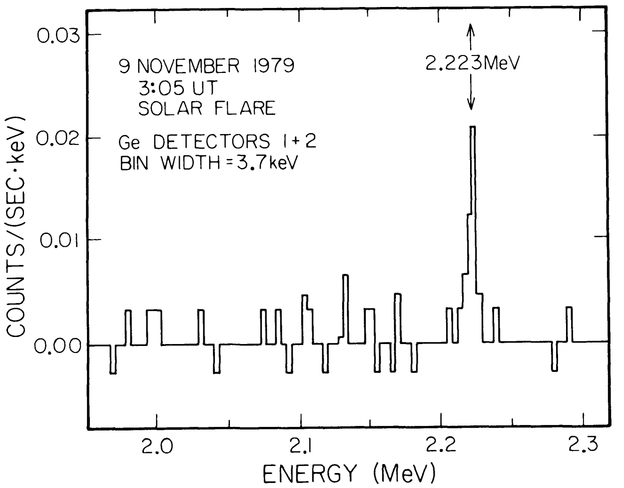

FIG. 2.—Energy response of the two germanium detectors on the sunward side of the spectrometer. The histogram shows a source minus background spectrum. The source period was 3:04:20–3:06:30 UT, while the background period was 3:01:20–3:04:00 UT.

The natural width of the 2.223 MeV line is expected to be very narrow, on the order of 100 eV (Ramaty *et al.* 1979). This is a consequence of the fact that the neutron capture takes place in the relatively cool photosphere where the effect of Doppler broadening is expected to be small. Figure 2 shows the γ-ray energy loss spectrum observed by the two germanium detectors on the sunward side of the instrument during the period between 3:04:20 and 3:06:30 UT which includes the time from the start of the γ-ray flare to the time of occultation. A background spectrum of equal time duration has been subtracted to give a net energy spectrum, and the count rates have been corrected for total live time. The width of the line feature is 6.8 keV FWHM, consistent with the instrumental resolution. The upper limit on the natural line width is 5 keV FWHM at the 82% confidence level, implying temperatures less than 20 million K, certainly consistent with neutron capture taking place in the photosphere. The energy of the line feature is 2.2248 ± 0.0010 MeV.

The average flux of 2.223 MeV photons over the 130 s period from the start of the flare to occultation was 0.29 ± 0.07 photons cm^{-2} s^{-1}. This compares to 2.2 MeV fluxes of 0.28 and 0.069 photons cm^{-2} s^{-1} seen from the large solar flares of 1972 August 4, 7 (Chupp, Forrest, and Suri 1975) and 1.0 photons cm^{-2} s^{-1} from the 1978 July 11 flare (Hudson *et al.* 1980). This is to be contrasted with the fact that the November 9 flare was a factor of 7–20 times shorter in duration than the earlier flares. The 2.223 MeV fluence in the November 9 flare was a factor of 3–10 times larger than in other flares of comparable duration seen by the *SMM* spacecraft during the recent solar maximum period (Chupp *et al.* 1981; Chupp 1981).

V. SUMMARY

We have presented in this *Letter* the first high-resolution measurement of nuclear γ-ray line emission from a solar flare. The observation unambiguously determines that the strong line feature observed is indeed the 2.223 MeV neutron capture line, based on a precise measurement of its energy, 2.2248 ± 0.0010 MeV. Time correlation of the line emission with lower energy (> 80 keV) continuum indicates that the time for the buildup of the neutron capture line is ≤ 20 s, consistent with the time of flight of MeV neutrons into the photosphere following production in the chromosphere or lower corona. The natural width of the line feature is ≤ 5.0 keV, also consistent with neutron capture in the photosphere.

The authors acknowledge helpful comments and suggestions from a number of colleagues including E. Chupp, H. Hudson, E. Stone, R. Vogt, and J. Willett. This work was carried out at the California Institute of Technology under NASA grant NGR 05-002-160 and at the Jet Propulsion Laboratory under NASA contract NAS 7-100.

REFERENCES

Chupp, E. L. 1982, in *Gamma-Ray Transients and Related Astrophysical Phenomena*, ed. R. E. Lingenfelter, H. S. Hudson, and D. M. Worrall (New York: American Institute of Physics), p. 363.
Chupp, E. L., Forrest, D. J., Higbie, P. R., Suri, A. N., Tsai, C., and Dunphy, P. P. 1973, *Nature*, **241**, 333.
Chupp, E. L., *et al.* 1981, *Ap. J.* (*Letters*), **244**, L171.
Chupp, E. L., Forrest, D. J., and Suri, A. N. 1975, in *IAU Symposium 68, Solar Gamma-, X-, and EUV Radiation*, ed. S. R. Kane (Dordrecht: Reidel), p. 341.
Hudson, H. S., Bai, T., Gruber, D., Matteson, J. L., Nolan, P. L., and Peterson, L. E. 1980, *Ap. J.* (*Letters*), **236**, L91.
Landecker, P. 1981, private communication.
Lingenfelter, R. E., and Ramaty, R. 1967, in *High Energy Nuclear Reactions in Astrophysics*, ed. B. S. P. Shen (New York: Benjamin Co.), p. 99.
Mahoney, W. A., Ling, J. C., Jacobson, A. S., and Tapphorn, R. M. 1980, *Nucl. Instr. Meth.*, **178**, 363.
Ramaty, R., *et al.* 1979, *Solar Flares, Proc. Skylab Solar Flare Workshop*.
Ramaty, R., Kozlovsky, B., and Lingenfelter, R. E. 1975, *Space Sci. Rev.*, **18**, 341.
Ramaty, R., Kozlovsky, B., and Suri, A. N. 1977, *Ap. J.*, **214**, 617.
Riegler, G. R., Ling, J. C., Mahoney, W. A., Prince, T. A., Wheaton, W. A., Willett, J. B., Zirin, H., and Jacobson, A. S. 1982, *Ap. J.*, submitted.
Ryan, J. M., *et al.* 1981, *Ap. J.* (*Letters*), **244**, L175.
Wang, H. T., and Ramaty, R. 1974, *Solar Phys.*, **107**, 1065.
______. 1975, *Ap. J.*, **202**, 532.

ALLAN S. JACOBSON, JAMES C. LING, WILLIAM A. MAHONEY, and GUENTER R. RIEGLER: Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91103

THOMAS A. PRINCE: California Institute of Technology, 220-47, Pasadena, CA 91125